

Cusp-core dichotomy of elliptical galaxies: the role of thermal evaporation

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Abstract

There are two families of luminous elliptical galaxies: cusp galaxies, with steep central surface-brightness profiles, and core galaxies, whose surface-brightness profiles have flat central cores. Thermal evaporation of accreted cold gas by the hot interstellar medium may be at the origin of this cusp-core dichotomy: in less massive (hot-gas poor) galaxies central cores are likely to be refilled by central starbursts following cold gas infall, while in more massive (hot-gas rich) galaxies most cold gas is eliminated and central cores survive. This scenario is consistent with the observation that cusp and core galaxies differ systematically in terms of optical luminosity, X-ray gas content, age of the central stellar population, and properties of the active galactic nucleus.

1 Introduction

There are two families of luminous elliptical galaxies: cusp galaxies and core galaxies. Cusp galaxies have steep power-law surface-brightness profiles down to the centre (hence the name “power-law” galaxies often used as a synonym of cusp galaxies), corresponding to intrinsic stellar density profiles with inner logarithmic slope $\gamma > 0.5$; core galaxies have surface-brightness profiles with a flat central core, corresponding to $\gamma < 0.3$ (Faber *et al.*, 1997; Lauer *et al.*, 2007). Cusp galaxies are relatively faint in optical, rotate rapidly, have disk isophotes, host radio-quiet active galactic nuclei (AGN) and do not contain large amounts of X-ray-emitting gas; core galaxies are brighter in optical, rotate slowly, have boxy isophotes, radio-loud AGN and diffuse X-ray emission (for a summary of these observational findings see Nipoti & Binney, 2007; Kormendy *et al.*, 2009, and references therein). The most popular explanation of the origin of such a dichotomy is that cusp galaxies are produced in dissipative, gas-rich (“wet”) mergers, while core galaxies in dissipationless, gas-poor (“dry”) mergers (Faber *et al.*, 1997), the cores being a consequence of core scouring by binary supermassive black holes (Begelman, Blandford & Rees, 1980). The actual role of galaxy merging in the formation of elliptical galaxies is still a matter of debate (e.g. Naab & Ostriker, 2009). What is reasonably out of doubt is that cores must be produced by dissipationless processes, while cusps are a signature of dissipation (Faber *et al.*, 1997; Kormendy *et al.*, 2009,

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and references therein). The dissipationless mechanism that forms the cores must not necessarily be scouring by binary black holes: even simple collisionless collapse may work (Nipoti, Londrillo & Ciotti, 2006). Dissipative processes must be invoked to explain the observed dichotomy because cusp galaxies are systematically less massive than core galaxies, and no purely stellar-dynamical mechanism can introduce a characteristic mass scale. An interesting question is therefore why the dissipative process responsible for the formation of cusps works in lower-mass ellipticals, but does not work in the most massive ellipticals. Nipoti & Binney (2007) argued that efficient thermal evaporation of cold gas by the hot interstellar medium of the most massive ellipticals can be at the origin of the cusp-core dichotomy. Here I briefly describe the basic principles of this scenario and discuss some implications for the properties of AGN in elliptical galaxies.

2 The formation of cusps and cores in elliptical galaxies

The stellar-dynamical process that forms the cores is expected to operate at all mass scales: it is therefore natural to start from the hypothesis that all ellipticals at some stage in their evolution have central cores. Such cores can be later refilled by central bursts of star formation, but a necessary condition for a central starburst to happen is the availability of cold gas in the inner galactic regions. Accretion of cold gas into galaxies, from minor mergers or cosmic infall, is believed to be common even at late times. If nothing prevents accreted cold gas reaching the galaxy centre, central starbursts are likely and the core can be easily refilled by a cusp. However, the journey of an accreted cold-gas cloud from the outskirts down to the centre of an elliptical galaxy might be not so safe. Massive elliptical galaxies are embedded in haloes of hot (virial temperature) gas, and the interaction of cold ($T \lesssim 10^4$ K) gas clouds with such a hot interstellar medium can disrupt the clouds via a combination of ablation and evaporation by thermal conduction. The motion of a cold gas cloud through a hot plasma is a complex dynamical process, involving heat conduction, radiative cooling, ram-pressure drag and ablation through the Kelvin-Helmholtz instability. Less massive clouds are more vulnerable, and it is possible to estimate with relatively simple analytic models a lower limit to the minimum mass a cloud must have to survive evaporation, depending on the temperature and density distribution of the hot interstellar medium (Nipoti & Binney, 2007). The total mass of cold gas available for central star formation is determined by the mass spectrum of accreted gas clouds and by the minimum mass for survival against evaporation. The aggregate mass of new stars formed as a consequence of cold infall is estimated to be proportionally larger in lower-mass (hot-gas poor) ellipticals than in higher-mass (hot-gas rich) ellipticals (Nipoti & Binney, 2007). Thus cores are likely to be refilled in the former, but not in the latter. This is consistent with the fact that all galaxies with high X-ray emission from hot gas

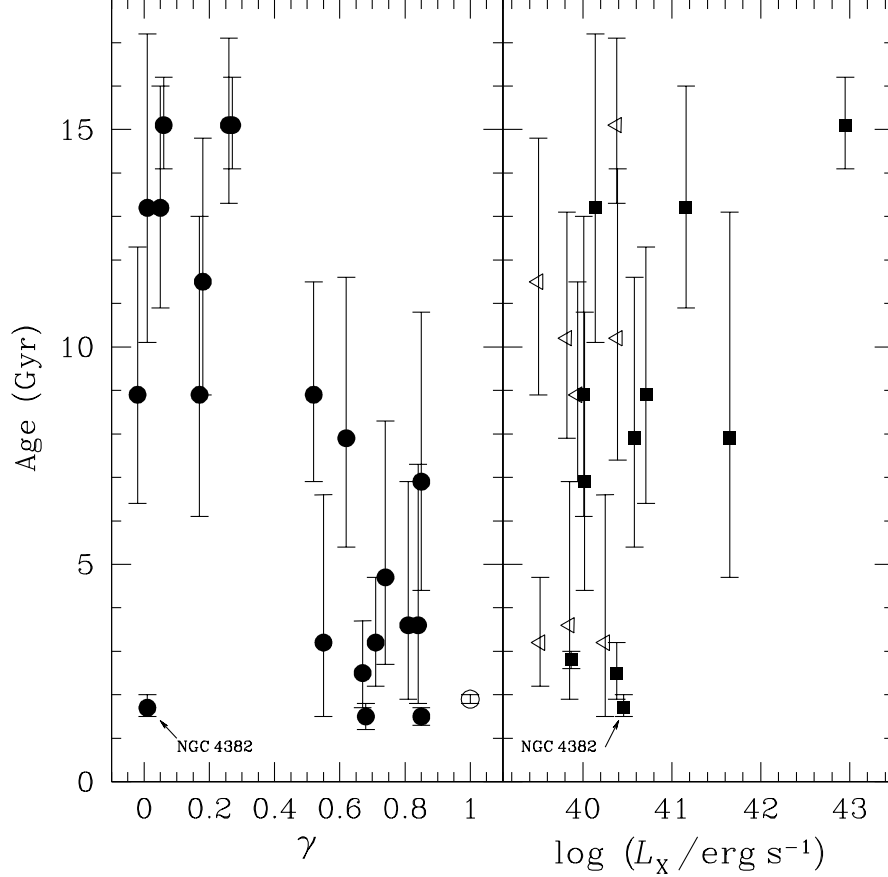


Figure 1: The age of the central stellar population versus the central slope of the intrinsic stellar density profile γ (left-hand panel; adapted from Nipoti & Binney, 2007) and versus the soft X-ray luminosity L_X (right-hand panel) for early-type galaxies studied by McDermid et al. (2006). Central ages (with error bars) are from McDermid et al. (2006), the values of γ are from Lauer *et al.* (2007) and the X-ray luminosities from Pellegrini (2005) and Ellis & O’Sullivan (2006). For not all the galaxies measures of both L_X and γ are available, so two slightly different sub-samples are represented in the left and right panels. In the right-hand panel solid squares represent detections and empty triangles upper limits in X-rays. The empty symbol in the left-hand panel represents NGC 4459, which is not in Lauer *et al.* (2007) sample, but is classified as a cusp galaxy by Kormendy *et al.* (2009): in the plot $\gamma = 1$ is assumed arbitrarily just to indicate that it is a cusp galaxy.

are core galaxies, while ellipticals with lower X-ray emission include both core and cusp galaxies (Pellegrini, 2005; Ellis & O’Sullivan, 2006).

If cusps are formed by late starbursts that refill a pre-existing core, the central stellar population in cusp galaxies must be relatively young. This prediction is nicely verified in the sample of early-type galaxies for which McDermid *et al.* (2006) estimated the age of the central stellar populations: in the plane of central age versus central logarithmic slope γ (Fig. 1, left-hand panel) early-type galaxies from this sample are found to be neatly segregated. Core galaxies have median central ages 13.2 Gyr, while cusp galaxies have median central age 3.6 Gyr (Nipoti & Binney, 2007). Given the known anti-correlation between γ and the soft X-ray luminosity L_X (galaxies with high L_X have $\gamma \lesssim 0.3$; Pellegrini, 2005; Ellis & O’Sullivan, 2006), it is interesting to see how galaxies from the same sample are distributed in the plane of central age versus L_X (Fig. 1, right-hand panel): consistent with the proposed scenario, there are no points in the bottom-right area of the diagram. In other words, among the galaxies of this sample, all those with young ($\lesssim 5$ Gyr) central stellar population have X-ray luminosity lower than $\sim 3 \times 10^{40} \text{ erg s}^{-1}$.

The only outlier of the bimodal distribution in the age-slope plane is the lenticular galaxy NGC 4382, which is classified as a core galaxy, but has young central stellar population (Fig. 1, left-hand panel). It must be noted that NGC 4382 is quite peculiar also in other respects: its very unusual morphology and surface brightness profile suggest to interpret it as an unrelaxed recent merger (Kormendy *et al.*, 2009). Moreover, the diffuse X-ray luminosity of NGC 4382 is relatively low (Sivakoff, Sarazin, & Irwin, 2003; Pellegrini, 2005), so the occurrence of a central starburst is not surprising. One might speculate that in NGC 4382 we are witnessing the first stages of the core-refill process.

3 Implications for active galactic nuclei in elliptical galaxies

Thermal evaporation may also have a role in determining the mode of accretion of central supermassive black holes in early-type galaxies. It is widely accepted that there are two main modes of black-hole accretion and feedback, usually referred to as “cold mode” (or QSO mode) and “hot mode” (or radio mode; e.g. Binney, 2005; Hardcastle, Evans & Croston, 2007). In the cold mode the black hole feeds from cold gas, close to the Eddington rate, and grows significantly in mass, with most of the energy released going into photons (optical, UV, X-ray). In the hot mode the black hole feeds from hot gas, at a rate much below Eddington’s, and does not grow significantly in mass, with most of the energy released being mechanical and generating significant radio emission. Bright QSOs and central radio sources in galaxy clusters are prototypes of the cold and hot modes, respectively, but the basic principles of this classification of the accretion modes apply to AGN in general.

In the proposed picture cold gas can be available for accretion onto the cen-

tral black hole only in cusp galaxies. Thus, all core galaxies must be hot-mode accretors, while cusp galaxies can be cold-mode accretors, when there has been a recent episode of cold gas infall into the galaxy. This is consistent with the findings that the optical nuclear emission (in units of the Eddington luminosity of the central black hole) is typically higher by two orders of magnitude in cusp galaxies than in core galaxies, that the nuclei of core galaxies are radio-loud, while those of cusp galaxies are radio-quiet (Capetti & Balmaverde, 2006; Balmaverde & Capetti, 2006), and that only core galaxies appear able to produce powerful extended radio emission (de Ruiter *et al.*, 2005). This model fits in a more general scenario in which radio-loudness is more controlled by the accretion mode than by black-hole spin, and hot-mode AGN, similar to the micro-quasars observed in our galaxy, during their lifetime alternate short bursts of radio-loudness with longer periods of radio-quiescence (Nipoti & Binney, 2005; Nipoti, Blundell & Binney, 2005).

4 Conclusions

Since the discovery of the cusp-core dichotomy of elliptical galaxies it has been proposed that cores are formed by dissipationless processes, such as binary black hole scouring, while cusps are formed by dissipative processes, such as merger-driven central starbursts (Faber *et al.*, 1997). This proposal is consistent with several observed properties of core and cusp galaxies, but does not explain *per se* why the most massive ellipticals are cored, while less massive ellipticals are cusped. A possible explanation is that all ellipticals originally have central cores: in less massive (hot-gas poor) ellipticals the cores are refilled by central starbursts following cold gas infall, while in more massive (hot-gas rich) ellipticals the cores are preserved because the hot interstellar medium ablates and evaporates most of the infalling cold gas (Nipoti & Binney, 2007). In this scenario black holes in core galaxies always accrete from hot gas, while black holes in cusp galaxies can accrete from cold gas, consistent with the observed properties of AGN in elliptical galaxies. The importance of the hot gas in preserving the cores in the most massive systems is supported by the state-of-the-art study of the early-type galaxies in the Virgo cluster by Kormendy *et al.* (2009).

In the present paper attention has been focused on the the role of thermal evaporation in determining the cusp-core dichotomy of elliptical galaxies, but elimination of accreted cold gas by the hot interstellar medium, via ablation and heat conduction, is likely to be a fundamental process for galaxy formation in general, as it may be at the origin of the truncation of the blue cloud and of the population of the red sequence in color-magnitude diagrams of galaxies (Binney, 2004; Nipoti & Binney, 2004, 2007). In this picture the role of black holes in quenching star formation is fundamental, but indirect: via AGN feedback they supply the hot gas with the energy necessary to evaporate the cold gas and thus quench star formation.

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